

Multi-Nanosecond High Power Pulse Generation at 7.8 GHz With a Dielectric-Loaded Power Extractor

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Abstract—Power extraction from charged particle beams is a prospective way to develop future high power radio frequency (RF) sources. We have designed and tested a 7.8 GHz power extractor based on a dielectric-loaded waveguide. Building upon earlier work on single electron bunch tests, 10 ns and 22 ns megawatt-level RF pulses have been generated with trains consisting of 16 electron bunches each, by using a laser splitting-recombination scheme. In addition, 44 MW of peak power has been generated with a train consisting 4 electron bunches. Behaviors of higher-order-modes are also explored.

Index Terms—Accelerator RF system, particle beams, pulse generation.

I. INTRODUCTION

HIGH power radio frequency (RF) sources play an important role in accelerator physics research. For particle colliders aiming at beam energy on the order of tera-electron-volt, such as the large hadron collider [1] and the proposed international linear collider [2], various high power RF sources have been extensively investigated, including the relativistic klystron [3], the gyroklystron [4], and the magnicon [5]. Aside from these traditional RF sources, two beam acceleration (TBA) has been studied [6]. It includes two stages: power extraction from a low-energy, high-current drive beam in the first stage, and acceleration of a high-energy, low-current beam in the second stage by the extracted power. The compactness of TBA may overcome difficulties in high power RF generation and transfer.

At the Argonne Wakefield Accelerator group (AWA), power extraction experiments based on circular dielectric-loaded (DL) waveguides have been carried out for the planned DL TBA [7], [8]. While maintaining similar accelerating gradient, the circular DL waveguide has a simpler geometry than conventional

disc-loaded accelerating structures. Hence it is more convenient to design and fabricate [9]. More effective suppression of harmful deflecting modes in the circular DL waveguide may also be possible [10].

Previous work [8] has provided the theoretical analysis on power extraction based on constant-impedance accelerating structures, design of the 7.8 GHz DL power extractor at AWA, and results of initial single bunch and bunch train tests where very short RF pulses (1–2 ns long) were generated. On one hand, in order to avoid difficulties in coupler design for very short pulse lengths, longer RF pulses are desired; on the other hand, to avoid possible breakdown caused by long pulses at high power, the pulse length needs to be limited. In this article, we will focus on generation of RF pulses that are tens of nanoseconds long with the use of laser splitting/recombination under precision timing control at the picosecond level.

The organization of the rest of the discussion is as follows: in Section II the 7.8 GHz power extractor and the setup for RF measurement are introduced; in Section III the laser beam splitting/recombination scheme is described; in Section IV the measurement results are displayed and analyzed; in Section V behaviors of high-order-modes (HOMs) are discussed; Section VI gives the conclusion.

II. THE 7.8 GHz POWER EXTRACTOR AND RF MEASUREMENT

When a charged particle beam passes through an accelerating structure, it will excite electromagnetic fields, i.e. wakefields. If no external power is applied, all the power flow in the structure comes from power loss of the particle beam, or in other words, the particle beam is decelerated by the structure. When a properly designed RF output coupler is added, the power excited by the particle beam can be extracted to accelerate another beam, thus comes the concept of *power extraction*.

At AWA, the 7.8 GHz DL power extractor is a constant impedance traveling-wave structure with a matched output coupler. It uses the 6th harmonic of the operation frequency (1.3 GHz) of the electron gun and the linac, with the TM_{01} mode being the deceleration mode. Fig. 1 shows the dimensions of the 7.8 GHz DL power extractor, whose detailed design is shown in [8]. It consists of a DL decelerating section (*decelerator*), and an RF output coupler specifically designed to convert the TM_{01} mode to the TE_{10} mode in a rectangular waveguide. The decelerator uses a dielectric tube made of Corderite with a relative permittivity of 4.6. The inner radius of the dielectric tube is 6.02 mm, the outer radius is 11.17 mm, and the total length of the decelerator is 266 mm (not completely shown in Fig. 1). The decelerator has a quality factor Q (including the metallic loss and the dielectric loss) of 2745. It needs to be

Manuscript received December 01, 2008; revised March 09, 2009 and March 20, 2009. Current version published June 17, 2009. This work was supported by the U.S. Department of Energy under Contract DE-AC02-06CH11357.

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Digital Object Identifier 10.1109/TNS.2009.2019749

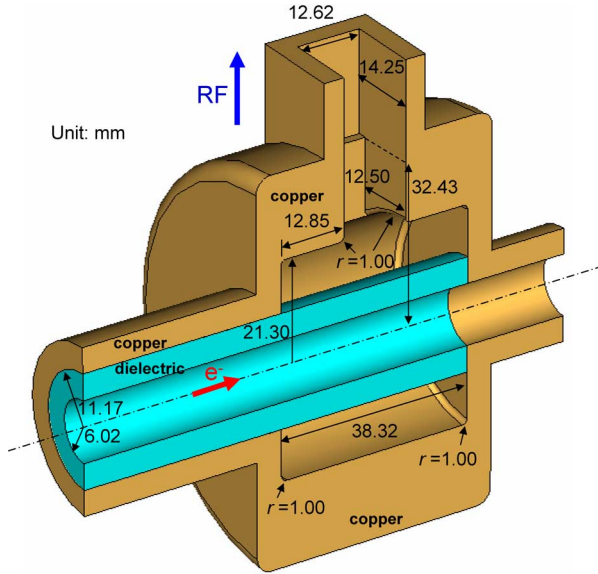


Fig. 1. Dimensions of the dielectric-loaded waveguide (on the left) and the RF output coupler (on the right). The wakefield power excited by an electron beam is extracted to a WR112 output waveguide by the RF output coupler.

mentioned that in a traveling-wave structure, the quality factor Q is defined as

$$Q = \omega U / P_{loss} \quad (1)$$

where ω is the angular frequency of the RF mode, U is time-averaged stored energy per unit length, and P_{loss} is the time-averaged power loss per unit length. The TM_{01} mode has an “ r over Q ” value of $6.09 \text{ K}\Omega/\text{m}$, where “ r over Q ” is the ratio of the shunt impedance per unit length to the quality factor defined as [11]

$$[r/Q] = E_a^2 / \omega U \quad (2)$$

where E_a is the magnitude of the on-axis longitudinal electric field (on-crest gradient) of the RF mode. The TM_{01} mode also has a group velocity of $0.23c$ and a phase velocity of c , where c is the speed of light in free space. At the downstream side of the decelerator, the dielectric tube extends into the copper cylinder of the RF output coupler, where the beam channel on the RF output coupler is beyond cutoff for the TM_{01} mode. A WR112 waveguide is used for RF output, which is located on the side wall of the copper cylinder, where a narrower section is used for impedance matching. The measured insertion loss (S_{21}) of the coupler is -0.41 dB at 7.8 GHz , implying 91% of the generated power can be extracted. From 7.69 GHz to 7.96 GHz the insertion loss is better than -1 dB , and from 7.67 GHz to 7.99 GHz it is better than -3 dB .

The generated power by an ultra-relativistic particle bunch train can be calculated as [8]:

$$P = q^2 \frac{k_z}{4\beta_g} \left[\frac{r}{Q} \right] \left(\frac{1 - e^{-\alpha_0 L}}{\alpha_0 T_b} \right)^2 \Phi^2 \quad (3)$$

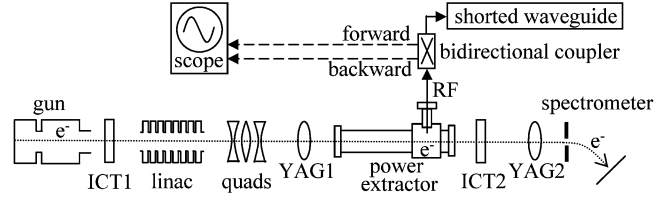


Fig. 2. Beamline setup for power extraction experiment.

where q is the charge per bunch, k_z is the longitudinal wave number of the deceleration mode, β_g is the relativistic group velocity, $[r/Q]$ is the quantity defined in (2), α_0 is the attenuation per unit length, L is the length of the decelerator, T_b is the bunch spacing, and Φ is the bunch shape factor. For a Gaussian bunch with an r.m.s. bunch length σ_z , the bunch shape factor can be simply calculated as:

$$\Phi = \exp \left[- (k_z \sigma_z)^2 / 2 \right]. \quad (4)$$

From both (3) and (4), and CST MAFIA [12] simulation, for a bunch train with bunch spacing of 769 ps and charge of 100 nC per bunch with 2 mm bunch length at the present AWA, 1.1 GW of power can be generated provided that the number of bunches is equal to or larger than 4. The power is proportional to the square of charge per bunch.

Fig. 2 shows the beamline setup for high power tests. The electron beam emerges from the gun at 8 MeV , and becomes accelerated to 15 MeV by the linac. The beam travels through the decelerator, monitored by integral current transformers (ICTs) and YAG screens. The final energy of the beam is monitored by a spectrometer. The RF power generated in the decelerator is extracted to the WR112 waveguide by the output coupler. It then goes through a -64.6 dB bidirectional coupler for detection. A shorted waveguide is used to delay the reflected signal for signal identification. Both the coupled forward and backward signals are measured by a 15 GHz oscilloscope (sampling rate: 40 Gs/s). Steering coils (not shown in the figure) and quads are used to maximize charge transmission.

III. LASER SPLITTING AND RECOMBINATION

In order to generate RF pulses with lengths on the order of tens of nanoseconds in the structure shown in Fig. 1, an electron bunch train is needed. At AWA, the electron beam is generated on a magnesium photocathode by an ultraviolet (UV) laser beam. Thus by splitting a single laser pulse into micropulses, and recombining them with different delays, one can generate the bunch train needed.

Fig. 3 shows the laser pulse splitting set, consisting of four 50/50 UV laser splitters (S1 to S4) and six UV laser mirrors (M1 to M6), with three arms to provide delays of $2T$, $4T$ and $8T$, where $T = 769 \text{ ps}$ is the period of the fundamental frequency 1.3 GHz . These mirrors are mounted on micrometers so that the delays can be finely adjusted. The single UV laser pulse is split into two trains consisting of 8 micropulses each (train A and train B), with a spacing of 1.538 ns between two adjacent

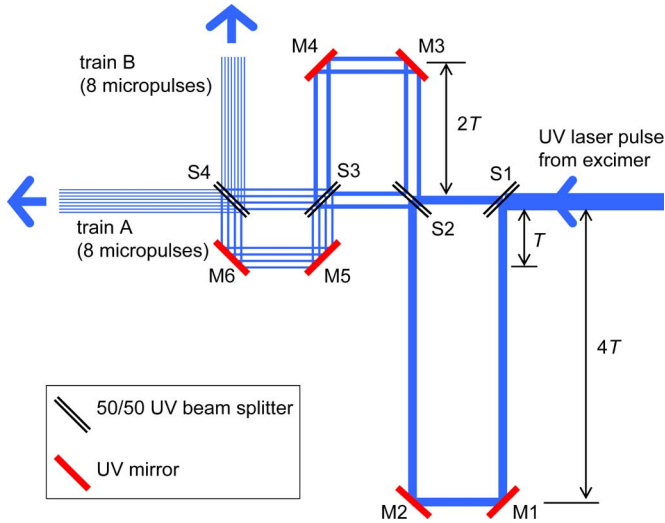


Fig. 3. The single laser pulse is split into two trains consisting of 8 micropulses each. The spacing between two adjacent micropulses is $2T = 1.538$ ns.

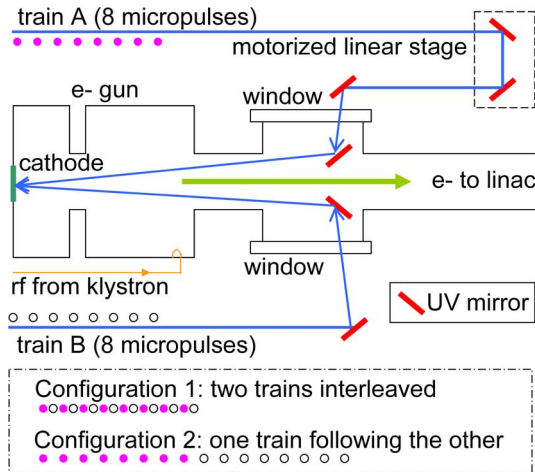


Fig. 4. Two different configurations for recombining the two trains of micropulses for different RF pulse lengths.

micropulses. It also needs to be mentioned that in Fig. 3 colinear laser beams are intentionally displaced for display.

Upon the action of the two trains of micropulses, electron bunch trains are generated with the setup shown in Fig. 4. The two trains of UV micropulses are sent into a cross chamber in the beamline through transparent windows on both sides. Then the two trains are reflected onto the center of the photocathode with UV mirrors. The path of train A has a motorized linear stage that can change the timing difference between train A and train B. Since the spacing inside each train is $2T$, when the two trains are interleaved, an electron bunch train with 16 bunches spaced by T is generated; on the other hand when one train follows the other, an electron bunch train with 16 bunches spaced by $2T$ is generated. The bunch train with a spacing of T has a shorter total length than that of the bunch train with a spacing of $2T$. However, from (3) the shorter train is able to generate power four times high as that generated by the longer one, since the bunch frequency $1/T_b$ of the former is only half of that of the latter.

One important step in the alignment procedure is to ensure the accuracy of the delays within each micropulse train shown in Fig. 3, and the delay between train A and train B during the recombination process shown in Fig. 4. Two different mechanisms were used for accurate timing control. For the delays inside each micropulse train shown in Fig. 3, the beam energy monitored by the spectrometer under low charge condition (~ 0.5 nC) was used for timing control. For example, ideally the electron bunch generated by the micropulse with path S1-S2-S3-S4 should have the same beam energy as that of the electron bunch generated by the micropulse with path S1-S2-S3-M5-M6-S4. The micrometer which carries the mirror pair M5-M6 is then finely tuned until the two electron bunches have the same beam energy. The fine tuning was limited to a round-trip step of 1 mm (~ 3 ps), since the splitting set is located in the beamline tunnel, thus each change needs a tunnel survey.

For the delay between train A and train B, the abrupt charge drop at 120° on the charge-versus-launching-phase curve was used as a reference point for timing control. In the beginning, the first micropulse in train B was set to this reference point where the generated charge barely becomes zero. By using the motorized linear stage, the first micropulse in train A was next brought to this reference point, enabling the two trains to have the same launching phase. This launching phase was varied by 1° of 1.3 GHz (~ 2 ps) to ensure the accuracy of the delay. After the adjustment was finished, the launching phase was changed back to $\sim 50^\circ$ for normal operation. Finally a beam energy check was conducted for each of the 16 electron bunches and it showed that the beam energy of all bunches was the same, indicating a electron bunch train that met the requirement was ready.

IV. MEASUREMENT RESULTS

With the setups described in Sections II and III, the generated power by electron beams was measured in the beamline. In addition to the -0.41 dB insertion loss of the RF output coupler and the -64.6 dB coupling coefficient of the bidirectional coupler, the cable from the bidirectional coupler to the oscilloscope contributed another 5.9 dB attenuation. Furthermore, depending on the strength of the detected signal, additional attenuators were used in some cases to protect the oscilloscope. The port impedance of the oscilloscope was 50Ω .

A. Generation of a 10 ns, 2.4 MW RF Pulse by a Train of 16 Electron Bunches Spaced by 769 ps

A train of 16 electron bunches spaced by 769 ps was generated, corresponding to Configuration #1 shown in Fig. 4. Beginning with a few bunches and eventually increasing to all 16 bunches, they were passed through the power extractor. The resultant detected signals are shown in Fig. 5. The actual charge was ~ 0.5 nC per bunch but the signal has been normalized to 1 nC per bunch for comparison. No attenuator was used, since the signals were just adequate. It can be clearly seen that as more consecutive bunches are used, the RF pulse becomes longer, while the voltage spectrum becomes narrower, centered at 7.8 GHz. Fig. 6 shows the generated power under different charges for the 16-bunch train with 769 ps bunch spacing. The measured data agrees very well with the simulated curve obtained from MAFIA [12] simulation, which agrees with the result from (3). The maximum power generated was 2.4 MW

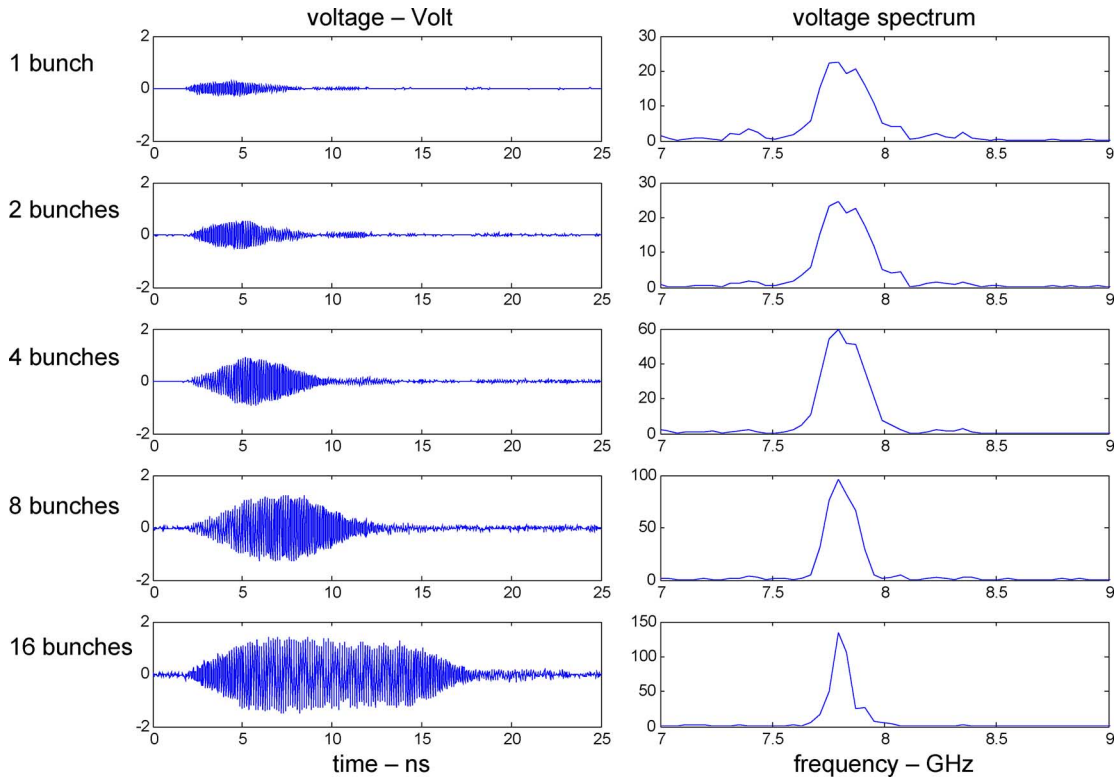


Fig. 5. Voltage signals generated by a train consisting 1–16 bunches spaced by 769 ps. Voltage is normalized to 1 nC per bunch.

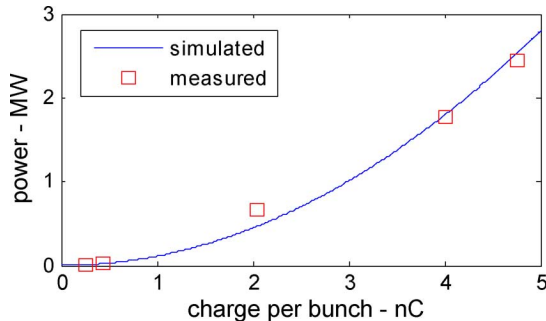


Fig. 6. Generated power versus charge for the 16-bunch train with 769 ps bunch spacing.

(2.2 MW extracted) with 4.8 nC of charge per bunch, where the flat-top RF pulse length was 10 ns. It needs to be mentioned that the simulated power generated with 4.8 nC per bunch is 2.58 MW, therefore the measured value is slightly less than the simulated one.

B. Generation of a 22 ns, 0.77 MW RF Pulse by a Train of 16 Electron Bunches Spaced by 1.538 ns

A train of 16 electron bunches spaced by 1.538 ns was generated in accordance with Configuration #2 shown in Fig. 4. First, train A and train B were passed through the power extractor separately. Then they were passed through altogether. Fig. 7(a) shows the measured voltage signals normalized to 1 nC per bunch, where a -13 dB attenuator was placed before the oscilloscope. When train A and train B were combined, the excited signals joined one another to form a longer forward signal

with 22 ns flat-top length (from $t = 5$ to $t = 27$ ns). After $t = 31$ ns, reflected signal from the shorted waveguide began to be detected. The voltage spectrum of the forward signal is shown in Fig. 7(b), which is narrower than that of the 10 ns RF signal detected with Configuration #1. Fig. 8 shows generated power under different charge levels for the 16-bunch train with 1.538 ns bunch spacing. The measured data agreed very well with the simulated curve obtained from MAFIA [12] simulation, which agrees with the result from (3). The maximum power generated was 0.77 MW (0.70 MW extracted) with 4.9 nC of charge per bunch. The simulated power generated with 4.9 nC per bunch is 0.67 MW, therefore the measured value is slightly higher than the simulated one. A possible reason is that some particles may hit the dielectric wall before exiting the beam channel, without being detected by the ICT2, therefore the actual charge may be underestimated.

C. Generation of 44 MW of RF Peak Power by a Train of 4 Electron Bunches Spaced by 769 ps

Because the quantum efficiency (QE) of the AWA magnesium photocathode is only on the order of 10^{-4} , charge generation is so limited that only ~ 5 nC of charge per bunch can be passed through with a train consisting of 16 bunches. Both theoretical analysis and simulation show that for the 769 ps bunch spacing with the number of bunches equal to or larger than 4, the generated power reaches the flat-top level. When more bunches are added, the pulse only become longer in length, not higher in power. This suggests that for limited UV pulse energy, if the pulse is only split into 4 micropulses, the generated 4 electron bunches with higher charge per bunch should be able to generate maximum power at the flat-top level.

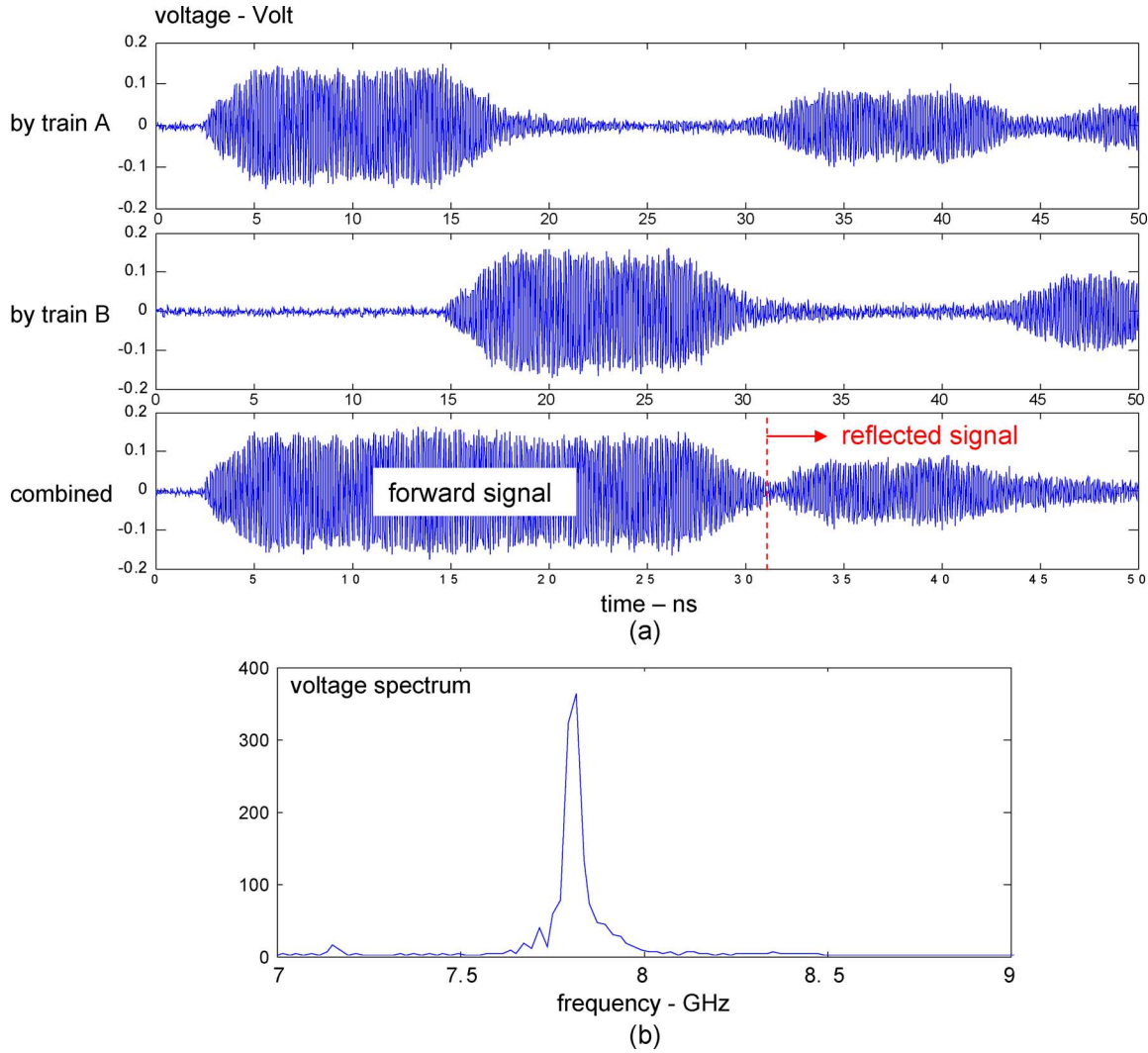


Fig. 7. Voltage signals generated by a train consisting 8 and 16 bunches spaced by 1.538 ns. Voltage is normalized to 1 nC per bunch and a -13 dB attenuator is used, (a) Signals generated by train A and train B when they are separated or combined; (b) the voltage spectrum of the total forward signal.

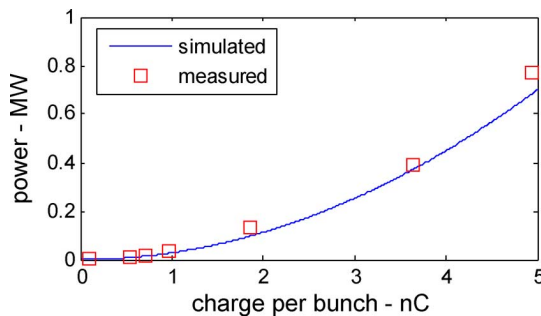


Fig. 8. Generated power versus charge for the 16-bunch train with 1.538 ns bunch spacing.

To obtain the four micropulse bunch train, the two beam splitters S1 and S2 were removed. Train A and train B were interleaved for 769 ps of bunch spacing. Fig. 9(a) shows the strongest voltage signal measured with a -30 dB attenuator, and Fig. 9(b) shows the voltage spectrum. From the voltage trace it can be calculated that 44 MW of power has been generated, 40 MW of which has been extracted, with charge of 26.75 nC per bunch.

The 44 MW generated power is substantially less than the simulated 80 MW with 26.75 nC per bunch. This is possibly related to strong space charge effects with an intense beam. This also indicates that with an intense beam, in order to reach the simulated power level which is calculated with an ultra-relativistic beam, effective beam-confining techniques such as a focusing-defocusing channel [13] may need to be employed.

V. DISCUSSIONS ON HOMs

When the electron beam passes through the DL waveguide, it excites not only the TM_{01} mode, but also higher order TM_{0n} modes ($n > 1$). In this experiment, the output coupler was specifically designed to only couple out power of the TM_{01} mode at 7.8 GHz, and there is no antenna in the decelerator, therefore no significant power of these HOMs was detected. Even so, discussions on HOM behaviors may still facilitate developing techniques for future power extractor design, such as suppression of unintended TM_{0n} modes.

The *synchronous frequencies* (at which the phase velocities are equal to c) of these HOMs are much higher than that of the TM_{01} mode, while the power of these HOMs generated in

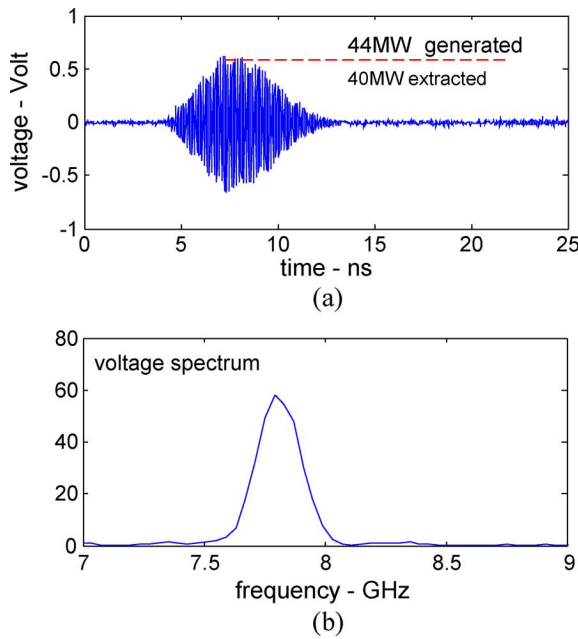


Fig. 9. Generation of 44 MW of maximum power by a 4-bunch train with 769 ps bunch spacing: (a) the measured voltage signal with a -30 dB attenuator before the oscilloscope; (b) the voltage spectrum.

the decelerator (not coupled out in this experiment) is usually lower than that of the TM_{01} mode due to lower $[r/Q]$ values and smaller bunch shape factors. For example, by solving the Maxwell's Equations with MathCAD [14], characteristics of the TM_{02} mode are obtained: the synchronous frequency $f_{TM_{02}}$ is 20.92 GHz, the " r over Q " $[r/Q]_{TM_{02}}$ is 1.97 K Ω /m, the group velocity $v_{gTM_{02}}$ is 0.305c, and the bunch form factor $\Phi_{TM_{02}}$ is 0.68. Since $f_{TM_{02}}$ is not an integer multiple of the bunch frequency $1/T_b$, with the detuning effect, the central frequency of the TM_{02} signal excited by a long bunch train (the number of bunches $N > 10$) will shift to the closest integer multiple of the bunch frequency 1.3 GHz, i.e. 20.8 GHz in this case. The generated power of the TM_{02} can be estimated as follows: firstly MAFIA [12] is used to probe the downstream gradient excited by a single bunch; secondly the gradient excited by $N(N > 10)$ single bunches are superposed with a temporal separation of T_b to obtain the longitudinal e-field (E_z) excited by a bunch train, where it can be seen the central frequency of the TM_{02} mode has shifted to 20.8 GHz; thirdly the TM_{02} signal is filtered out from the bunch train signal to obtain the E_z signal of the TM_{02} mode; finally from the relation of the amplitude of E_z and power flow of the TM_{02} mode at 20.8 GHz (calculated with CST Microwave Studio [15]) one can calculate the generated power. In this way the generated power of the TM_{02} mode was estimated to be 305 MW with charge of 100 nC per bunch. It needs to be mentioned that if T_b is changed to 765 ps (corresponding to a bunch frequency of 1.307 GHz, the 16th sub-harmonic of 20.92 GHz), the power calculated above would be 370 MW. From the two power levels (305 MW and 370 MW) it can be seen that for the TM_{02} mode the power generated in the detuning case is $305/370 = 82.4\%$ of that in the non-detuning case.

In this 7.8 GHz power extractor, only the TM_{01} mode is useful while the other TM_{0n} ($n > 1$) modes are unintended.

To improve the efficiency of power conversion from the drive beam to the intended mode, suppression of unintended mode is necessary. A technique to suppress these unintended modes is being investigated and will appear in future publications.

VI. CONCLUSIONS

By power extraction employing a DL waveguide with laser pulse splitting/recombination executed at the picosecond level, 10 ns and 22 ns high power RF pulses have been generated. In addition, 44 MW of maximum power has been reached in bunch train tests. This laser splitting/recombination scheme is potentially useful for RF pulse shaping, since the RF pulse shape is determined by the structure of the laser micropulse trains, which can be easily controlled by placing neutral-density filters in the laser paths.

A cesium telluride photocathode with a QE higher than 10^{-2} is being developed at AWA, which is expected to generate at least 50 nC of charge per bunch for a train consisting of 16–64 electron bunches. In addition, a second 1.3 GHz linac is planned to be added into the beamline, which is expected to accelerate the electron beam to 25 MeV. When the new photocathode and the new linac are commissioned, 10–50 ns RF pulses in excess of 100 MW can be expected from this power extraction scheme.

Finally, characteristics of HOMs in power extraction are also discussed. A technique to suppress these unintended modes is under investigation.

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